Directions in studies pA at RHIC =
High energy cold nuclear matter phenomena

How pA at RHIC can complement pA at LHC

Mark Strikman, PSU

- Nuclear pdfs - first direct evidence for gluon LT shadowing
- ✔ Leading hadron production disentangling shadowing, effective energy losses,...
- ▲ Color fluctuations, conditional pdfs

Important benchmark measurement of ALICE [arXiv:1305.1467]

Ultraperipheral production of J/ψ: $\gamma + A \rightarrow J/\psi + A$

$x = m^2_{J/\psi}/s = 10^{-3}$

Evidence for nuclear gluon shadowing from the ALICE measurements of PbPb ultraperipheral exclusive J/ψ production

[arXiv:1305.1724]

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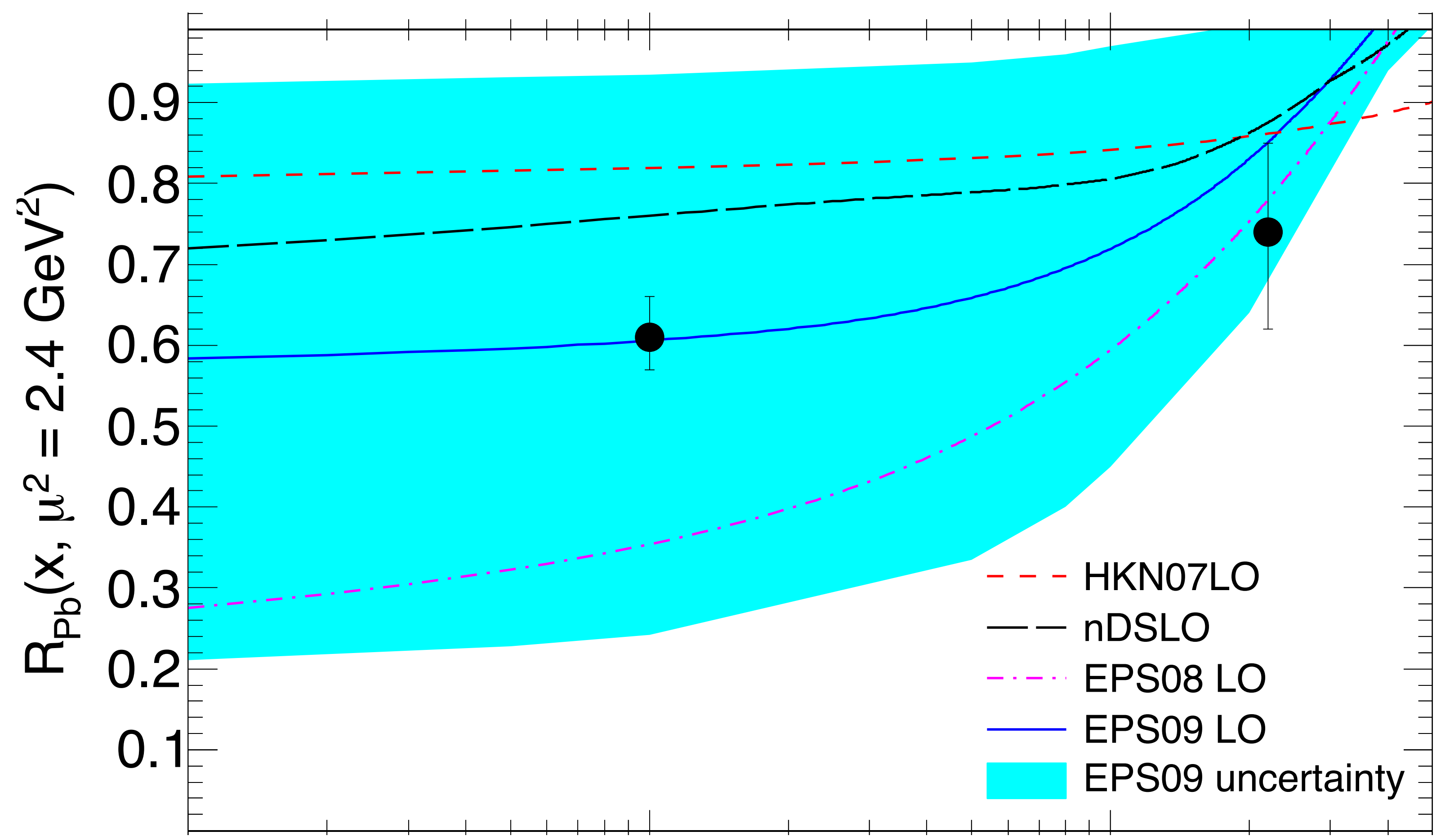
Derive from the data suppression factor $R(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})} \right]^{1/2}$

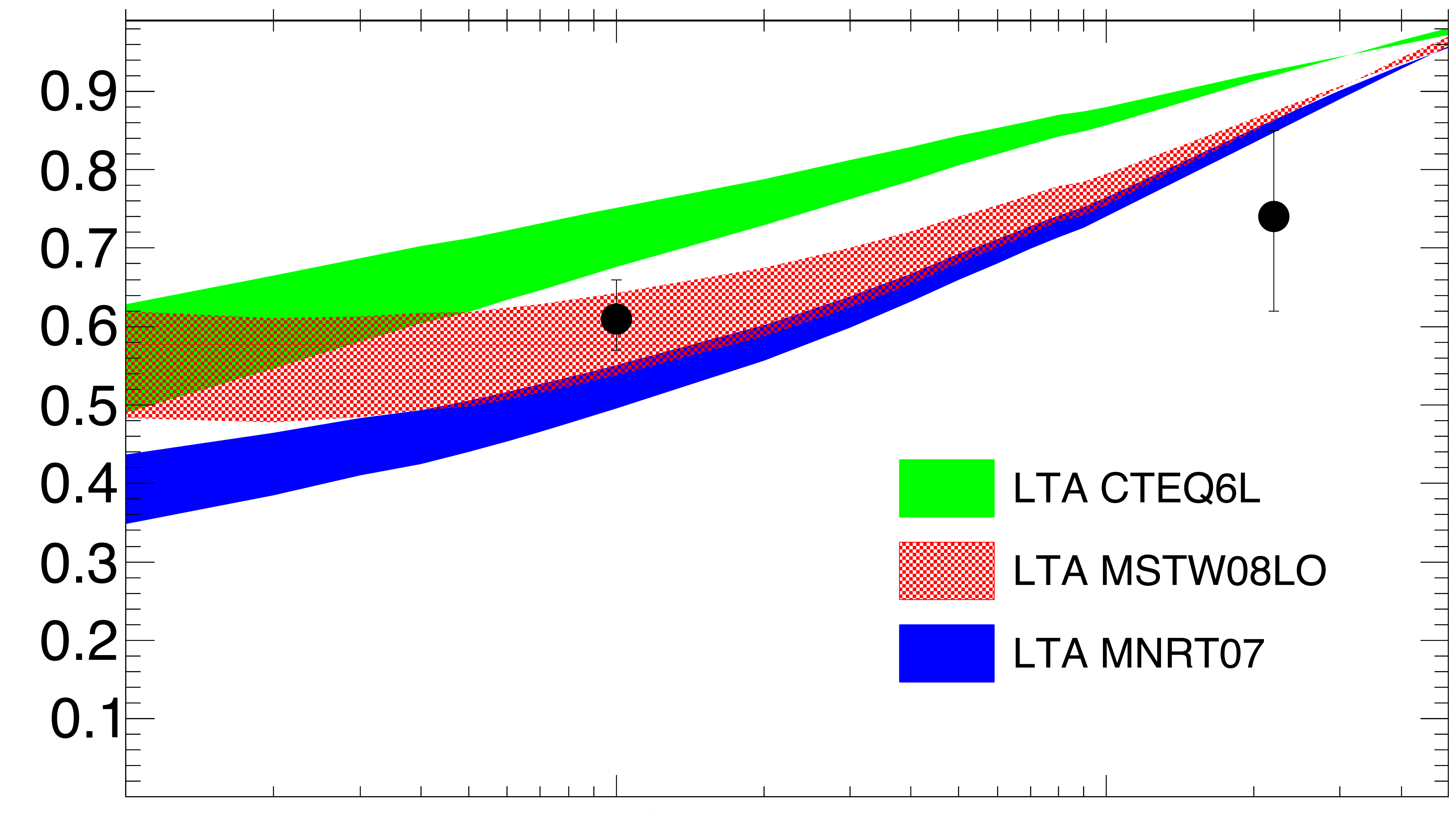
$R = 0.61^{+0.05}_{-0.04}$

Brodsky et al(94): $$R=\left[\frac{d\sigma^{\gamma^*+A\to VM+A}(t=0)}{dt}\Big/\frac{d\sigma^{\gamma^*+p\to VM+p}(t=0)}{dt}\right]^{1/2}=\frac{G_A(x,Q^2_{eff})}{AG_N(x,Q^2_{eff})}$$

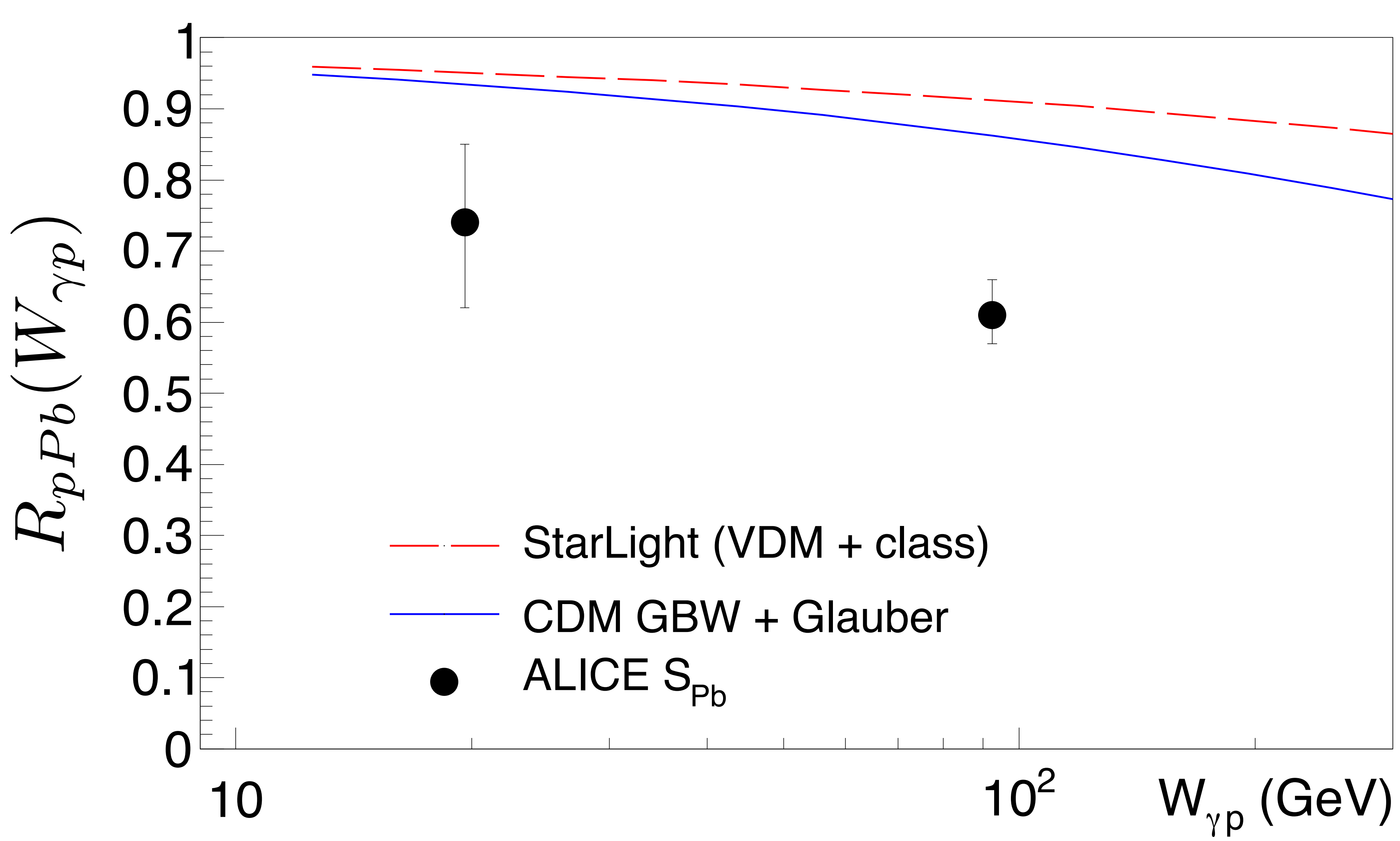
LT shadowing --Prediction of large suppression of J/ψ photoproduction at $x \sim 10^{-3}$ based on the theory of the leading twist shadowing. Dipole model with eikonal rescattering much smaller suppression



Fits to previous data + extrapolation: huge uncertainties.



Main uncertainty is due to poor knowledge of $g_N(x,Q)$ for $Q^2 \sim 2.5\ GeV^2$



Glauber model with the color dipole cross section and eikonal schadowing mechanism and in the Starlight approach very small suppression

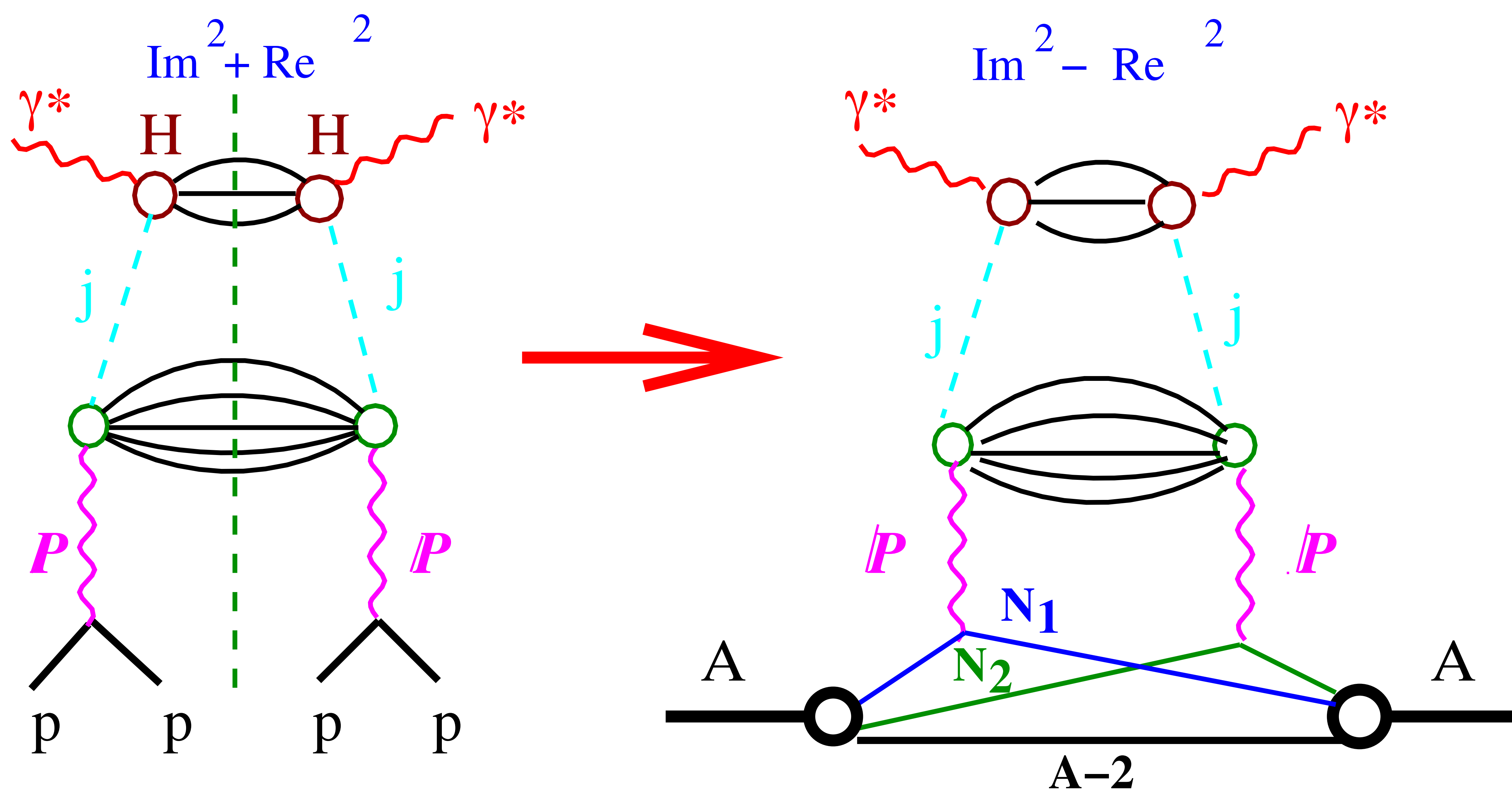
Theoretical expectations for shadowing in the LT limit

Physics Reports 512 (2012) 255–393

L. Frankfurt [a], V. Guzey [b,*], M. Strikman [c]

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98) (instead of calculating F_{2A} only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$



Hard diffraction

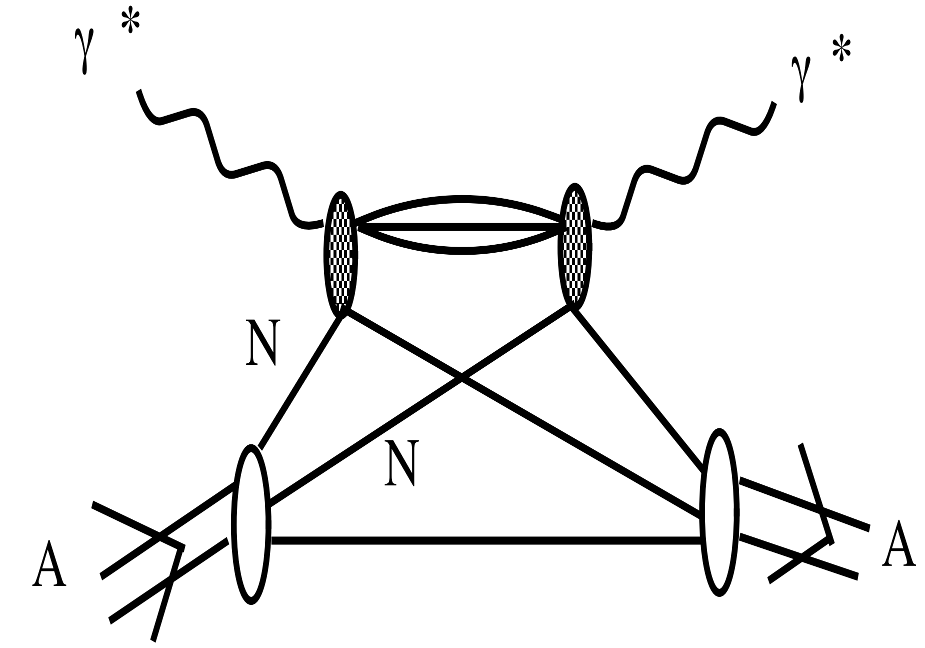
off parton "j"

Leading twist contribution

to the nuclear shadowing for

structure function $f_j(x,Q^2)$

Including higher order terms



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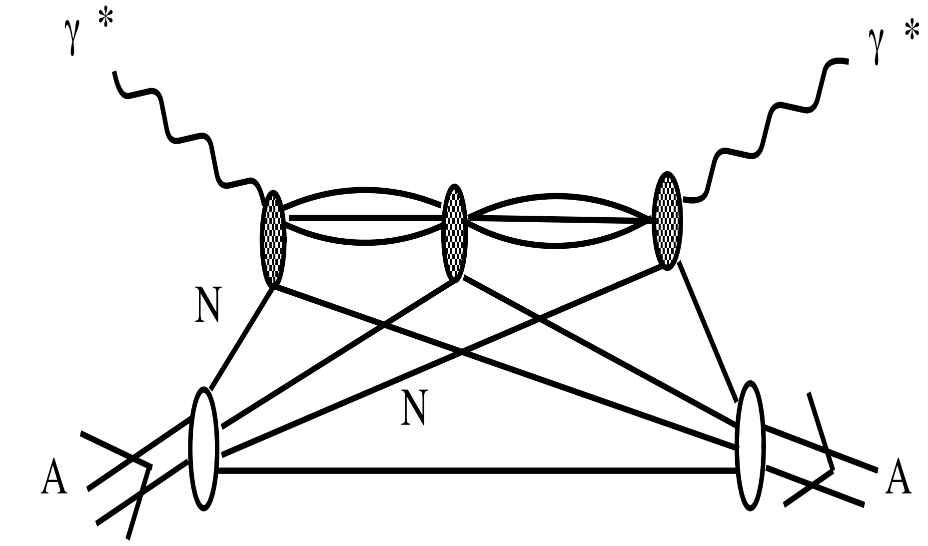


+ ....

Color fluctuation approximation: Amplitude to interact with j nucleons $\sim\sigma^j$

$$x f_{j/A}(x,Q^2) = \frac{x f_{j/N}(x,Q^2)}{\langle\sigma\rangle_j} 2\,\Re e \int d^2b \left\langle \left(1 - e^{-\frac{A}{2}(1-i\eta)\sigma T_A(b)}\right)\right\rangle_j$$

$$= A x f_{j/N}(x,Q^2) - x f_{j/N}(x,Q^2)\frac{A^2\langle\sigma^2\rangle_j}{4\langle\sigma\rangle_j}\Re e(1-i\eta)^2 \int d^2b\, T_A^2(b)$$

$$- x f_{j/N}(x,Q^2) 2\Re e \int d^2b \frac{\sum_{k=3}^{\infty}(-\frac{A}{2}(1-i\eta)T_A(b))^k \langle\sigma^k\rangle_j}{k!\,\langle\sigma\rangle_j},$$

does not depend on f_j

$\langle \ldots \rangle_j$ integral over σ with weight $P_j(\sigma)$ - probability for the probe to be in configuration which interacts with cross section σ;

$$\langle\sigma^k\rangle_j = \int_0^\infty d\sigma P_j(\sigma)\sigma^k$$

For intermediate x one needs also to keep finite coherence length factor $e^{i(z_1 - x z_2) m_N x_{I\!P}}$

Fluctuations with small σ are significant only for $\langle\sigma\rangle$, $\langle\sigma^2\rangle$

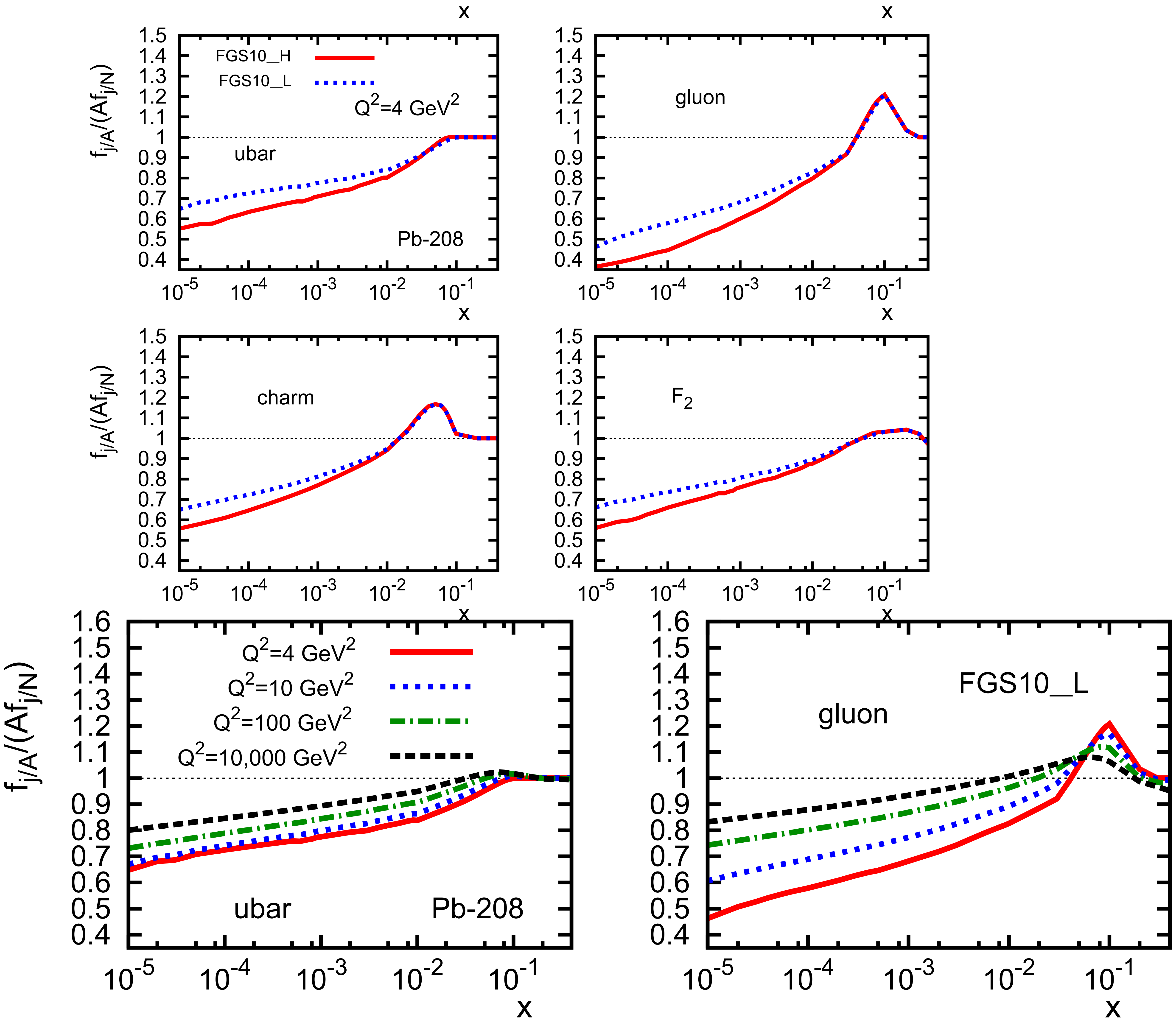
$\langle\sigma^k\rangle$ for $k > 2$ dominated by soft fluctuations. $\alpha_{I\!P}(0)=1.1$ - proof that soft dynamics dominates already for $\langle\sigma^2\rangle$

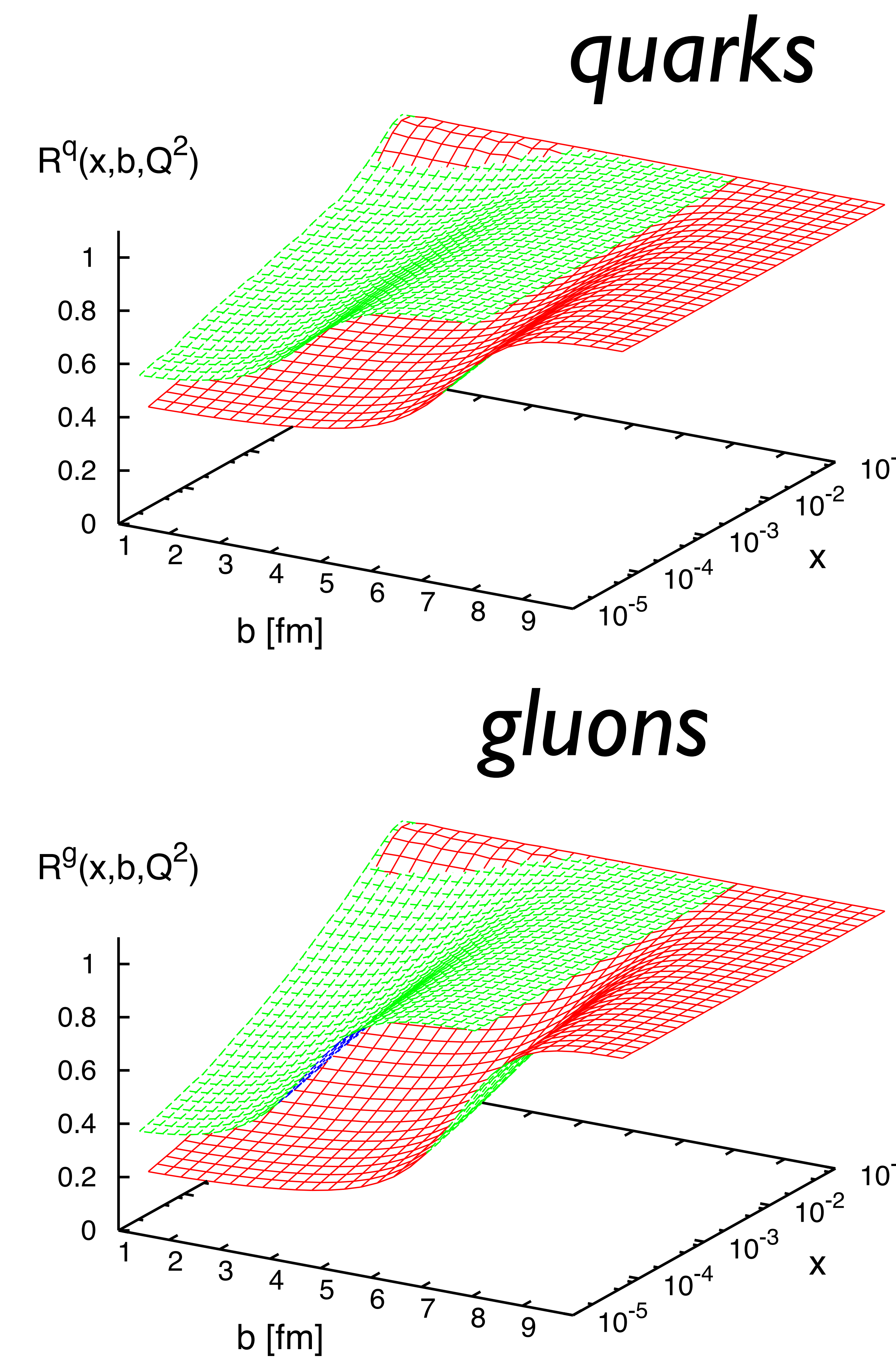
$\langle\sigma^k\rangle / \langle\sigma^2\rangle$ can be modeled based on soft physics - effects of dispersion in this case known to be small (we did a numerical study for our case where these effects are larger due to presence of small configurations).

Fluctuation approximation for Q_0^2:

$$
\begin{aligned}
& x f_{j/A}(x,Q^2) = A x f_{j/N}(x,Q^2) \\
& - x f_{j/N}(x,Q^2) 8\pi A(A-1)\, \Re e \frac{(1-i\eta)^2}{1+\eta^2} B_{\rm diff} \int_x^{0.1} dx_{I\!P} \beta f_j^{D(3)}(\beta, Q^2, x_{I\!P}) \\
& \times \int d^2 b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1-z_2) x_{I\!P} m_N} e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}(x,Q^2) \int_{z_1}^{z_2} dz' \rho_A(\vec{b}, z')}
\end{aligned}
$$

where $\sigma_{soft}(x,Q_0^2) \equiv \left\langle\sigma^3\right\rangle_j / \left\langle\sigma^2\right\rangle_j$ is the only parameter (weakly dependent on x) which can be estimated semiquantitatively.





Impact parameter dependence of nuclear shadowing for ^{40}Ca (upper green surfaces) and ^{208}Pb (lower red surfaces). The graphs show the ratio $R_j(x,b,Q^2)$ as a function of x and the impact parameter |b| at $Q^2 = 4$ GeV^2.

Shadowing increases with decrease of x
(cf. EKS09 guess: flat at small x)

First data confirm expectation of the LT theory that cold nuclear matter parton density differs strongly from the sum of nucleon densities at least for x ~ 10^{-3} and below. More data are expected from LHC on small x region, in particular LHCb down to x~ 10^{-5}

Implications for RHIC - in the forward region one can probe x down to 10^{-4} and hence check factorization. Likely to be broken for x_p's close to the edge of the phase space (will discuss later) and expect rather large effects. In principle at lower energies one can probe smaller virtualities where modifications are stronger: Forward Drell- Yan ?

All analyses of processes which involve small x gluons like forward inclusive J/ψ production **must include effect of LT gluon shadowing**. Large/ dominant effect for forward J/ψ production in pA at LHC (LHCb data).

Forward pion production at RHIC: Summary of the challenge

☞ For pp - pQCD works both for inclusive pion spectra and for correlations

☞ Suppression of the pion spectrum for fixed p_t increases with increase of η_N.

Independent of details - the observed effect is a strong evidence for breaking of LT pQCD approximation. Natural suspicion is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.

The key question: what is the mechanism of the suppression of the dominant pQCD contribution of quark scattering off gluons with $x_A > 0.01$ where shadowing effects are very small. Note also that shadowing on the scale observed by ALICE gives very small contribution to suppression in LT.

CGC scenario - assumes ☟ LT $x_A > 0.01$ mechanism becomes negligible, though experimentally nuclear pdf = A nucleon pdf for such x (assumes that somehow suppression of the LT mechanism should be >> than observed suppression of inclusive spectrum), ✌ $2 \to 1$ mechanism dominates

Post-selection scenario - LT $x_A > 0.01$ mechanism is suppressed but still *dominates inclusive cross section*

✔ *Post-selection (effective energy losses) in proximity to black disk regime (BDR)* - usually only finite energy losses discussed (BDMPS) (QCD factorization for LT) - hence a very small effect for partons with energies 10^4 GeV in the rest frame of second nucleus. Not true in black disk regime - post selection - energy splits before the collision - effectively 5- 15 % energy losses decreasing with increase of k_t. at $k_t > k_t(BDR)$ Large effect on the pion rate since x_q's, z's are large,

$$\Downarrow$$

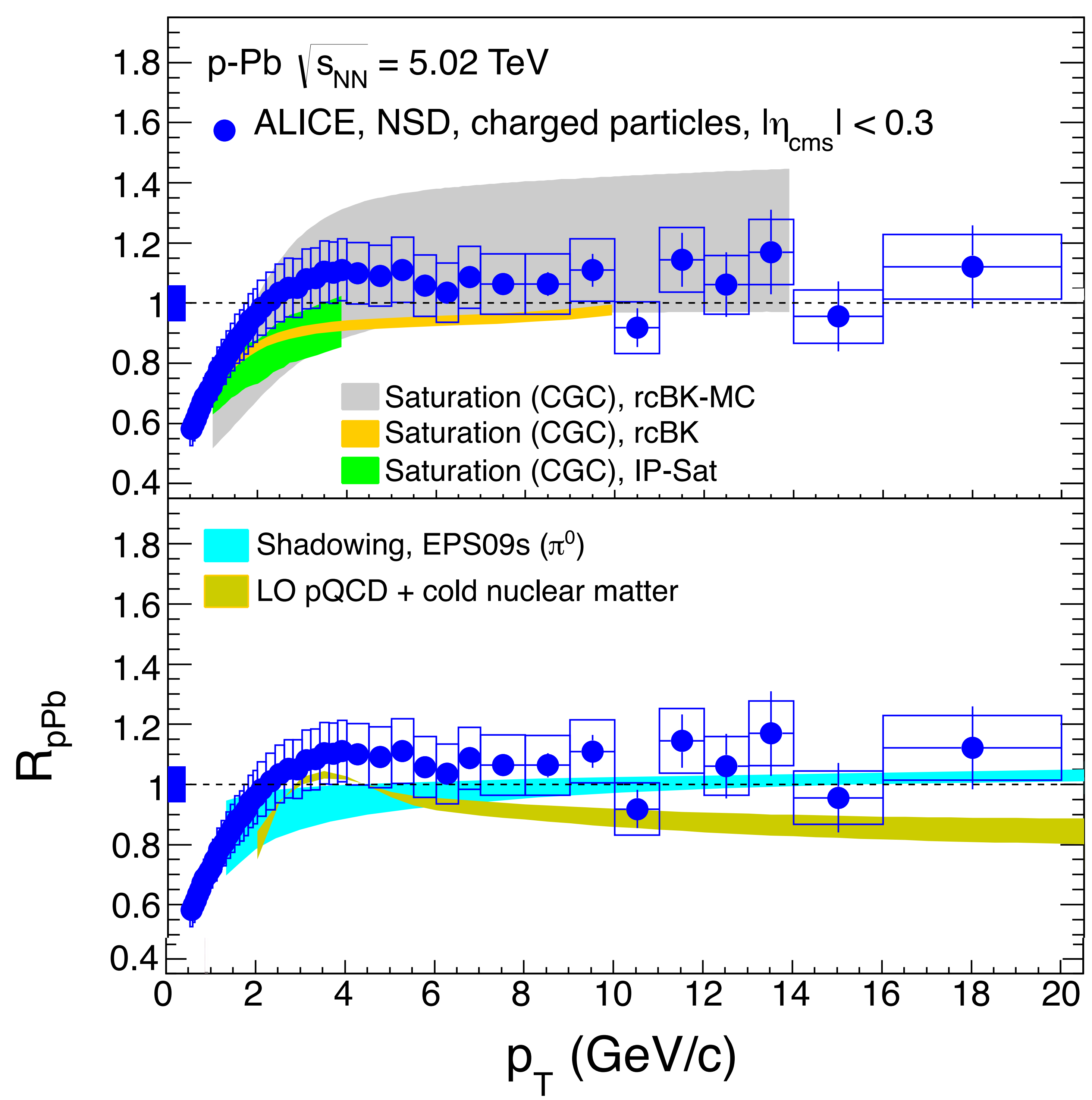
Dominant yield from scattering at peripheral impact parameters.
Hence a modest reduction of polarized effects like A_N

$$\Downarrow$$

Post-selection is a large effect only for large x_F. At small x_F p_t broadening a more prominent effect. Hence effect easier to observe at RHIC than at the LHC.

RHIC correlation data appear to rule out CGC 2 → 1 mechanism as a major source of leading pions in inclusive setup ⇒ NLO CGC calculations of inclusive yield grossly overestimates 2 → 1 contribution.

Also, so far no evidence for a strong suppression in pA (LHC) for the same / larger invariant parton - nucleus energy. If saturation gives little at LHC it should give little for RHIC as well for the same effective s !?



Leading hadron production in the central pA(pp) collisions

Expectation: The leading particle spectrum should be strongly suppressed in the central pA collisions as compared to minimal bias pp collisions since each leading parton gets large transverse momentum and hence fragments independently and may also split into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons. This model neglects additional suppression due to finite fractional energy losses in BDR

$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\to h+X} = \sum_{a=q,g}\int dx\, x f_a^{(p)}(x, Q^2_{\rm eff}) D_{h/a}(z/x, Q^2_{\rm eff})$$

The limiting curve of leading particles from hadron-nucleus collisions at infinite A

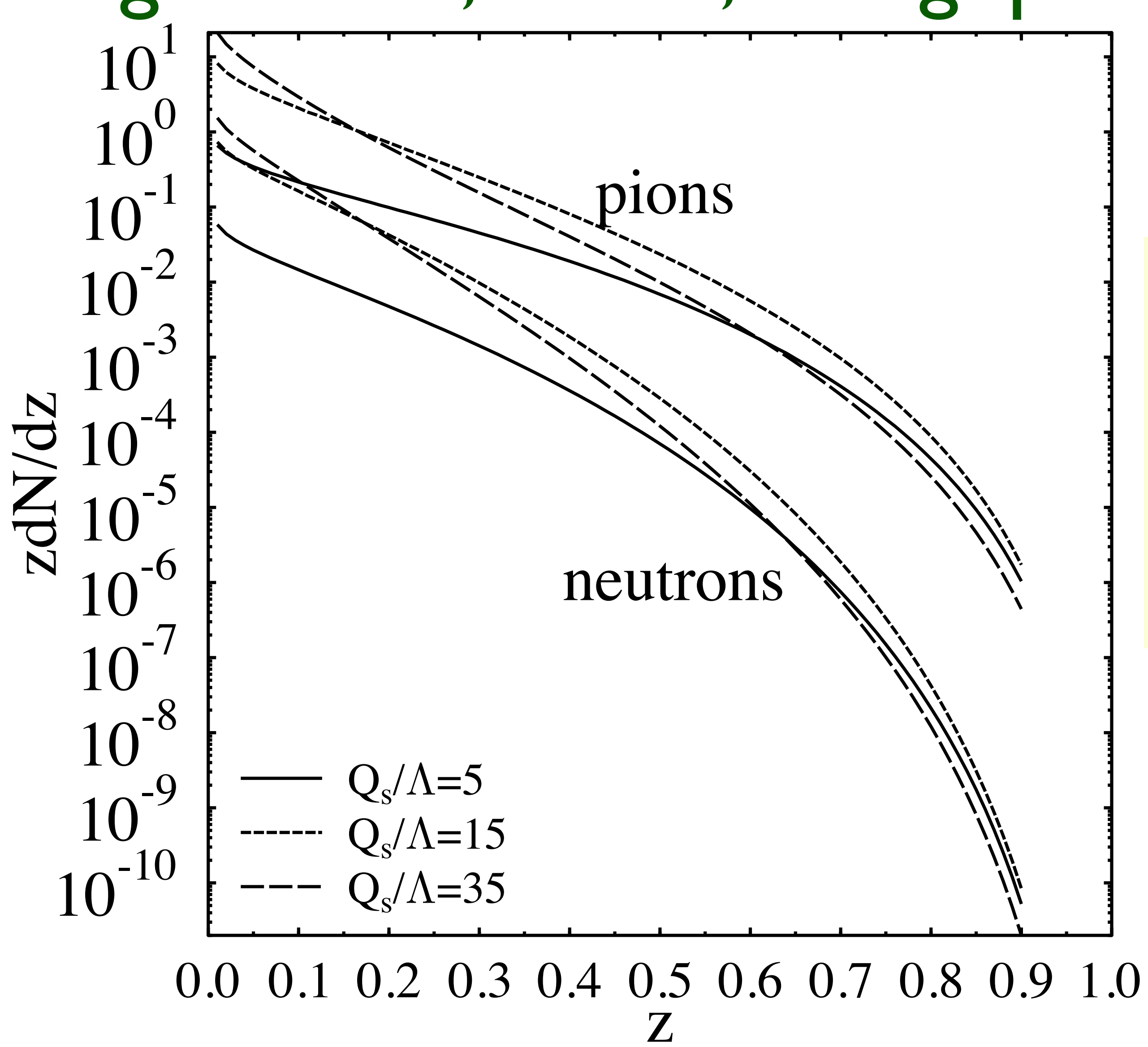
A. Berera[a,1], M. Strikman[a], W.S. Toothacker[b], W.D. Walker[c], J.J. Whitmore[a]

Physics Letters B 403 (1997) 1–7

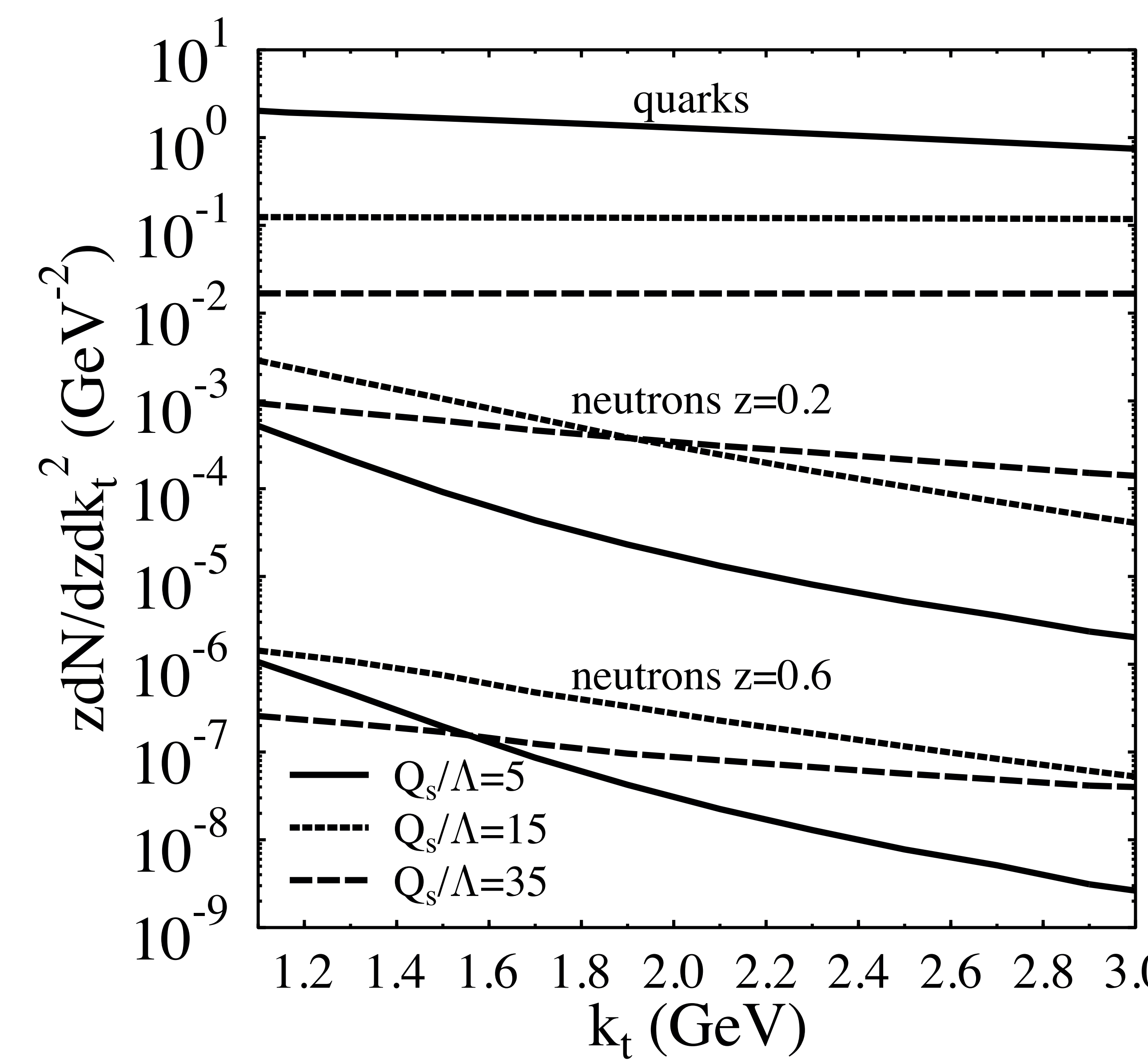
Simple model of p_t broadening - eikonal rescattering model with saturation (Boer, Dumitru 2003), effective energy losses (mentioned before) are neglected

$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp\left(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}\right) .$$

Quark gets a transverse momentum of the order Q_s but does not loose significant energy (account would strengthen the effect) Use of the convolution formula for fixed transverse momentum of the produced hadron using $C(k_t)$ - Dumitru, Gerland, MS -PRL03. Other calculations with similar logic -Gelis, Stasto, Venugopalan (06)



Steep fall with z, strong E_{inc} dependence

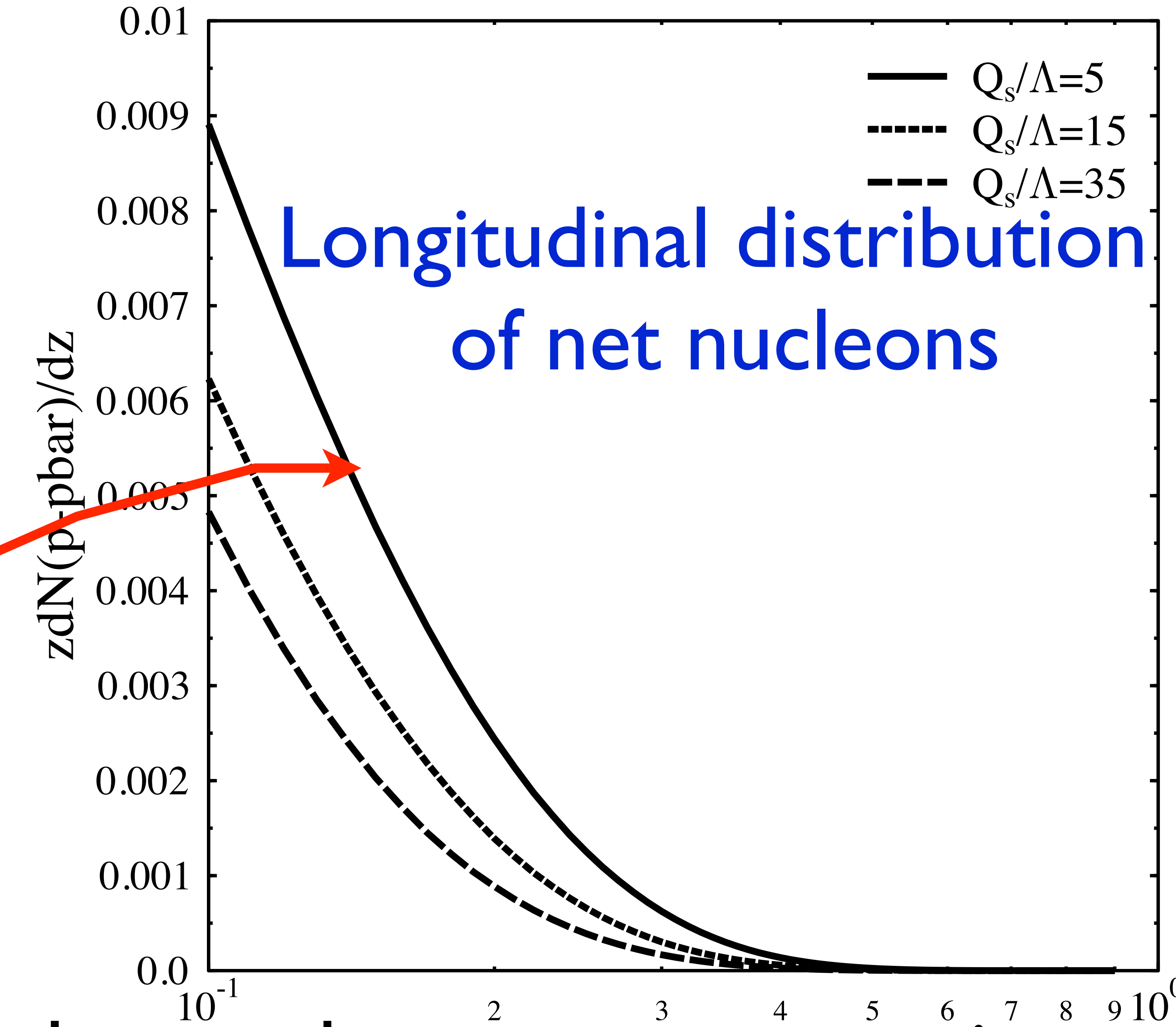


Weak p_t dependence, becomes weaker with increase of E_{inc}

Longitudinal (integrated over p_t) and transverse distributions in CGC model for central pA collisions.

Spectra for central pp - the same trends. Qualitative feature shared by all models -- suppression should grow with energy for fixed x_F, and p_t distribution should broaden.

Very few forward baryons in central collisions!!!



Large flow of energy to central rapidities
- obvious implications for AA

Warnings: Parton carrying a fraction y of the quark momentum carries $y\, p_t$ part of the quark's transverse momentum. Condition for independent fragmentation $y\, p_t > 1/r_N \sim .3 - 0.5$ GeV/c

For RHIC (LHC) independent fragmentation is probably safe for $z > 0.2$ (0.1)

➡ Photon - proton contribution has to be subtracted!!!

Experimental prospects (perhaps too optimistic for LHC)

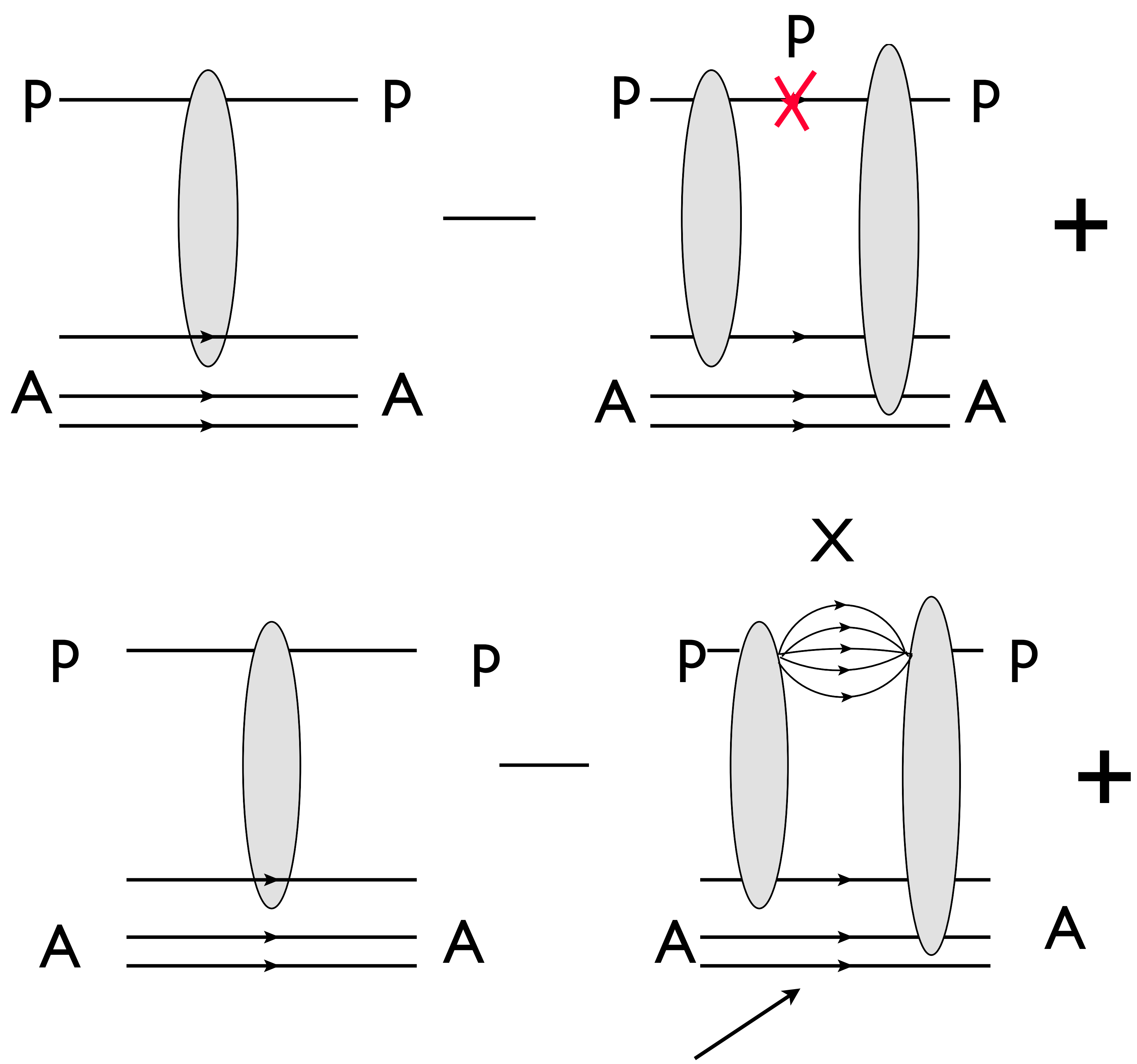
pA run at LHC: TOTEM: $x_F \geq 0.8$ broad range of p_t can check both suppression and p_t broadening neutrons from ZDC (CMS, ALICE, LHCf); π^0+ (LHCf) -large z , moderate p_t

RHIC: will allow pA runs at different energies and for several nuclei to avoid model dependent procedure for determining centrality of collision. Spin effect for neutrons ??? LHCf LOI for RHIC - nice way to compare pA at LHC and RHIC.

Warning: Color fluctuations in nucleon and nucleon density in nucleus may reduce the suppression

COLOR FLUCTUATIONS & CONDITIONAL PDFs

High energy space-time picture of soft pA - Gribov - Glauber fundamentally different from low energy Glauber picture



$$\sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p+p \to p + X(p + \ inel \ diff))}{dt}$$

Glauber model

in rescattering proton in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov)- no time for a proton to come together between nucleons. Violates energy conservation for cut through two exchanges

High energies = Gribov -Glauber

X= set of intermediate states the same as in pN diffraction

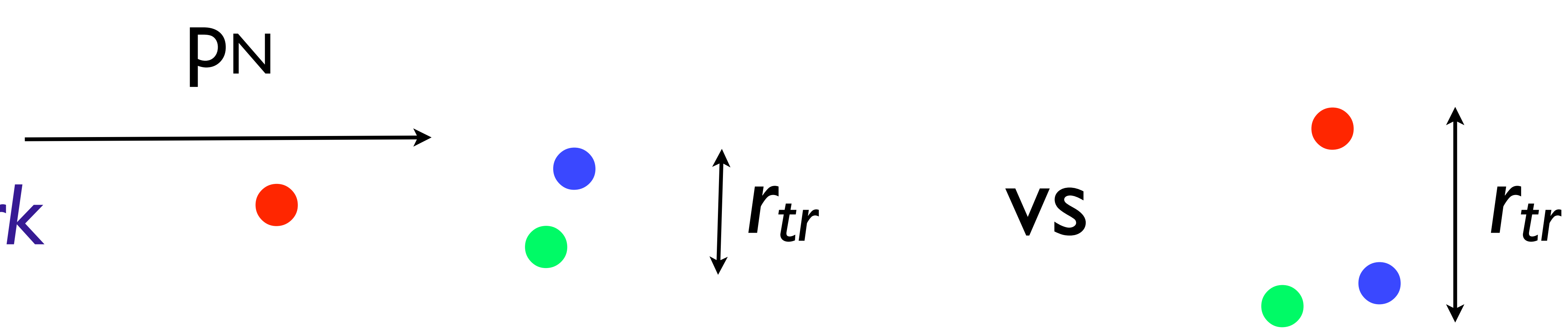
Deviations from Glauber for $\sigma_{tot}(pA)$ are small for Einc ~ 10 GeV as inelastic diffraction is still small. They stay small for heavy nuclei for all energies. But for pD at ISR at large t effect is large ~40%. An effective way to implement Gribov-Glauber picture of high energy pA interactions is the concept of color fluctuations

Color fluctuations in the nucleon wave function & 3-dimensional mapping of the nucleon

Are there global fluctuations of the strength of interaction of a fast nucleon, for example due to fluctuations of the size /orientation. Extreme case - color transparency.

$$|N\rangle = 3q + 3qg + 3q + \pi + \ldots$$

proton= quark + diquark



Due to a slow space-time evolution of the fast nucleon wave function one can treat the interaction as a superposition of interaction of configurations of different strength - Pomeranchuk & Feinberg, Good and Walker, Pumplin &Miettinen. In QCD this is reasonable for total cross sections and for diffraction at very small t.

Convenient quantity - $P(\sigma)$ -probability that nucleon interacts with cross section σ.

$\int P(\sigma)d\sigma = 1$, $\int \sigma P(\sigma)d\sigma = \sigma_{tot}$,

$$\frac{\frac{d\sigma(pp\to X+p)}{dt}}{\frac{d\sigma(pp\to p+p)}{dt}}\Bigg|_{t=0} = \frac{\int(\sigma-\sigma_{tot})^2 P(\sigma)d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma$$

variance

Pumplin &Miettinen

$\omega_\sigma(RHIC)=0.25$ $\omega_\sigma(LHC)=0.20$ - more data are coming from LHC

A very rough model illustrating scale of the effect

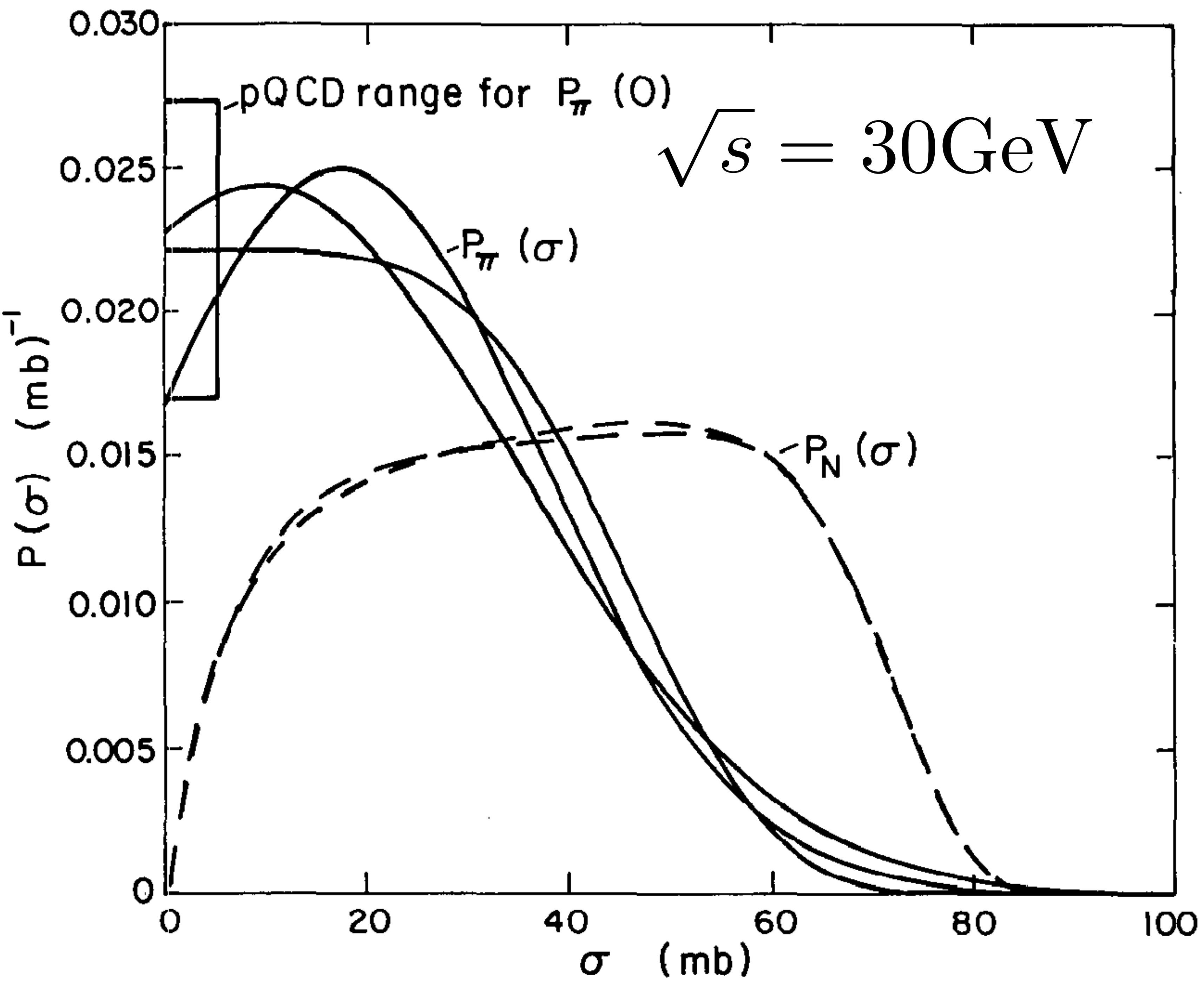
$$P(\sigma) = \frac{1}{2}\delta(\sigma-\sigma_{tot}(1-\sqrt{\omega_\sigma})) + \frac{1}{2}\delta(\sigma-\sigma_{tot}(1+\sqrt{\omega_\sigma}))$$

for RHIC $\omega_\sigma=0.25$, $\sigma_1=0.5\sigma_{tot}$; $\sigma_2=1.5\sigma_{tot}$ for LHC $\omega_\sigma=0.2$ (0.1?), $\sigma_1=60$mb ; $\sigma_2=140$mb

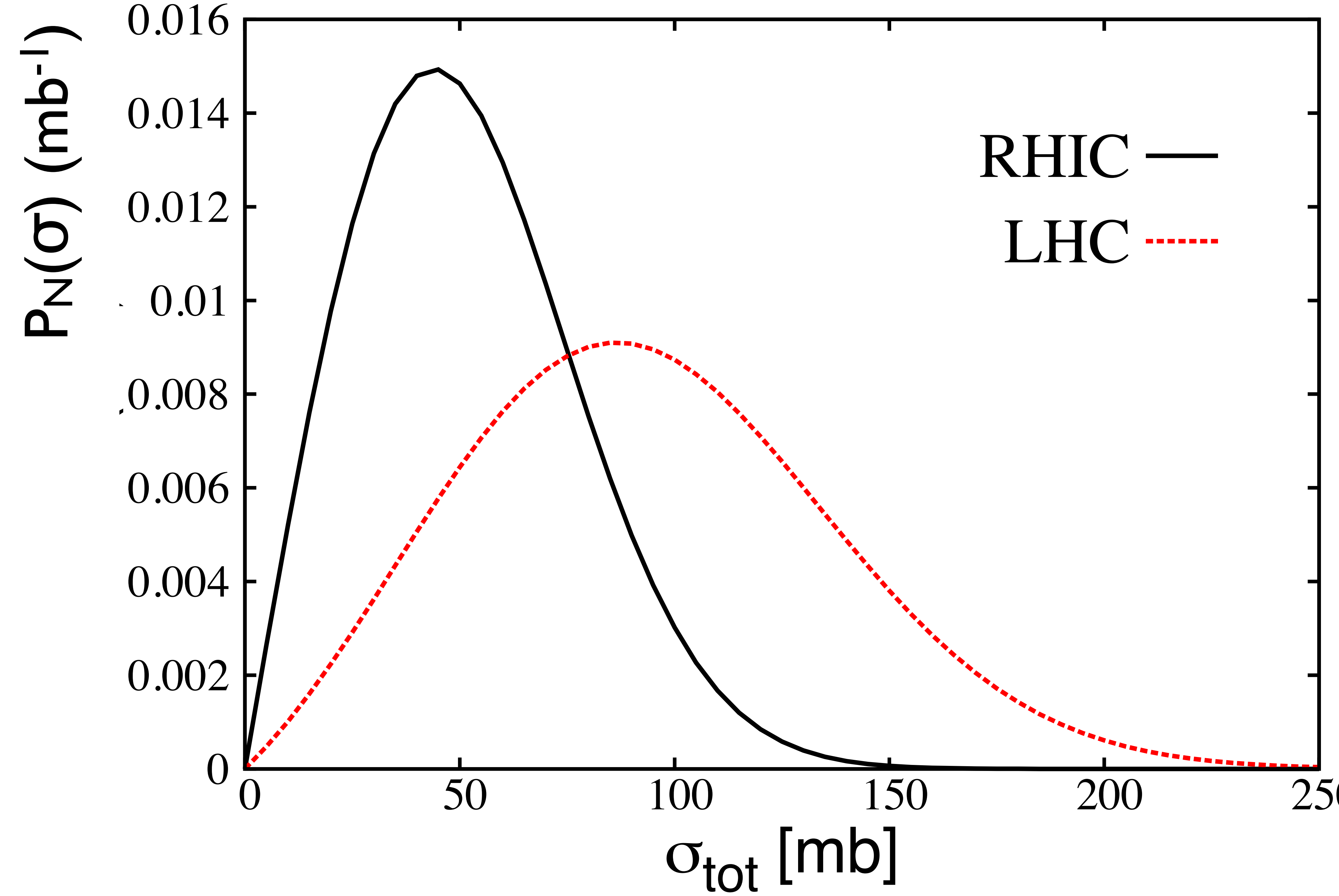
$\int (\sigma - \sigma_{tot})^3 P(\sigma)d\sigma = 0$, Baym et al from pD diffraction

$$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q-2}$$

Baym et al 1993

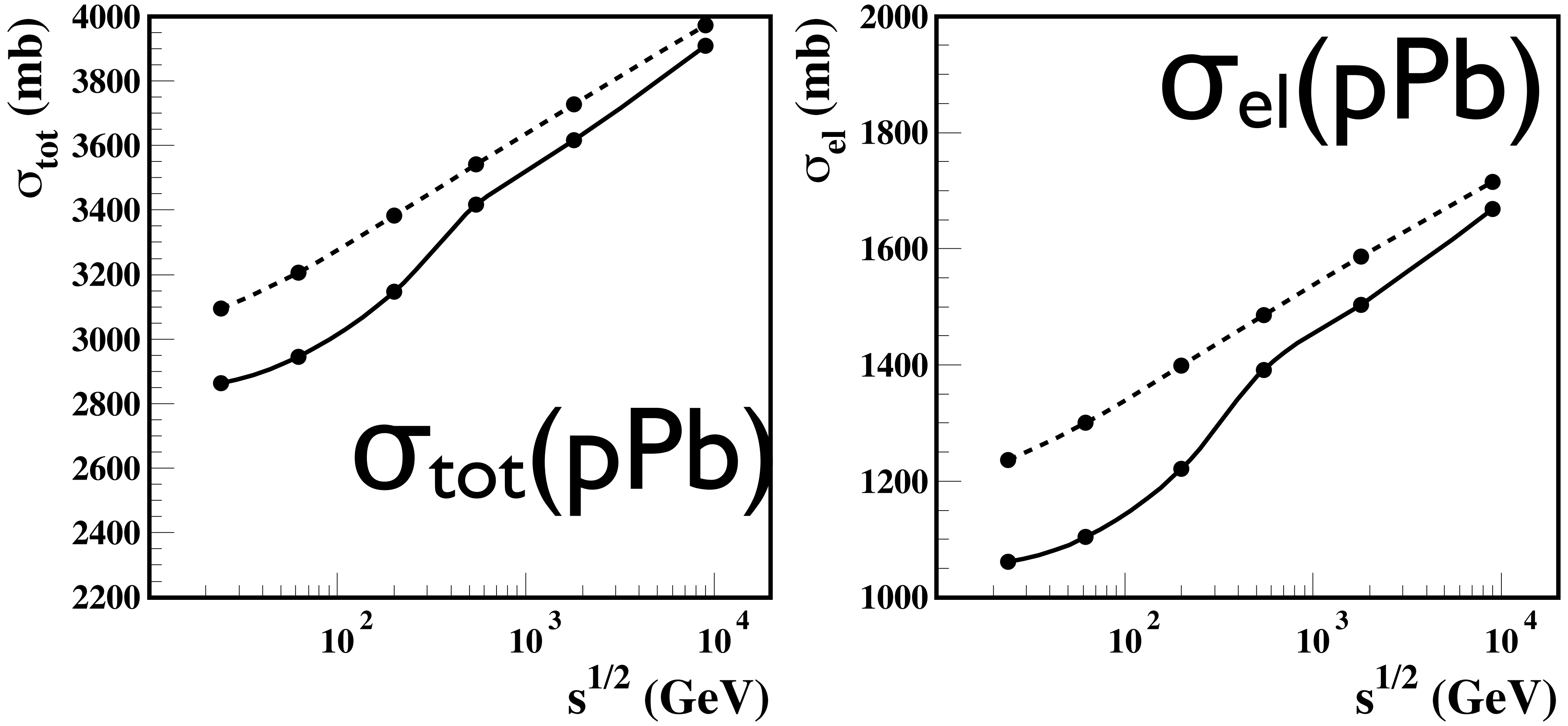


$P_N(\sigma)$ extracted from pp,pd diffraction Baym et al 93. $P_\pi(\sigma)$ is also shown



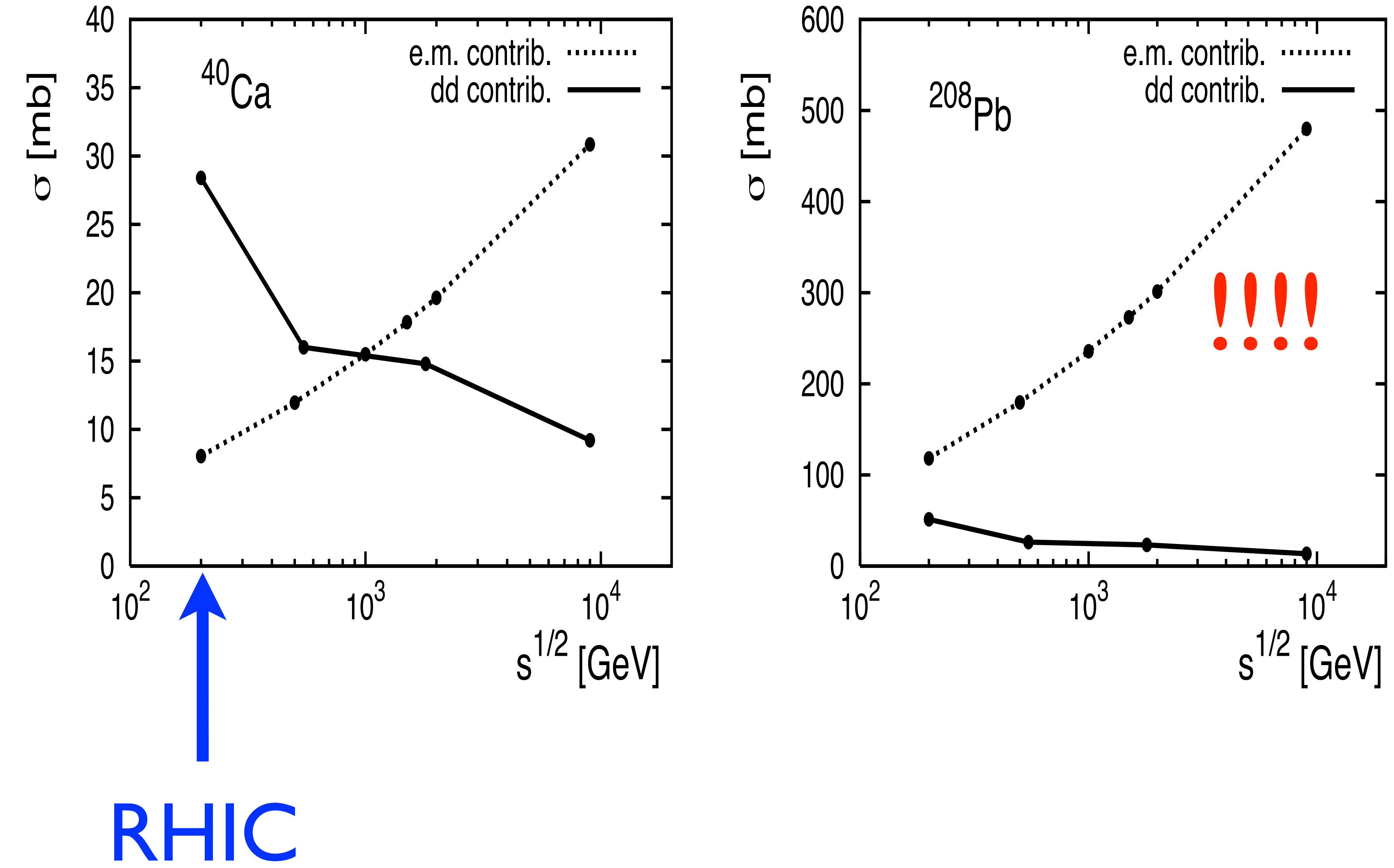
Extrapolation of Guzey & MS to higher energy using diffractive data

Color fluctuations/inelastic shadowing



Guzey & MS

$\sigma_{diff}(pA \to XA)$



$\Rightarrow$ E.M. interaction dominates by far in diffraction above RHIC energies

true for hard diffraction as well (Guzey, MS)

$\Rightarrow$ For RHIC for A=200 comparable contributions, for A=40, e.m. contribution is a small correction. A unique opportunity for RHIC. Use ZDC to suppress break up?

Numerical calculations (Alvioli and MS) - event generator using our sets of nucleon configurations in nuclei with short-range correlations (small effect) and finite radius of NN interaction.

For NN scattering $P_{inel}(\rho) = 1 - |1 - \Gamma(\rho)|^2$

We also took σ/B= const for fluctuations (corresponding to σ_{el}/σ_{tot}=const)

$$P_h(\sigma_{tot}) = r\,\frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0}\, exp\{-\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2}\}$$

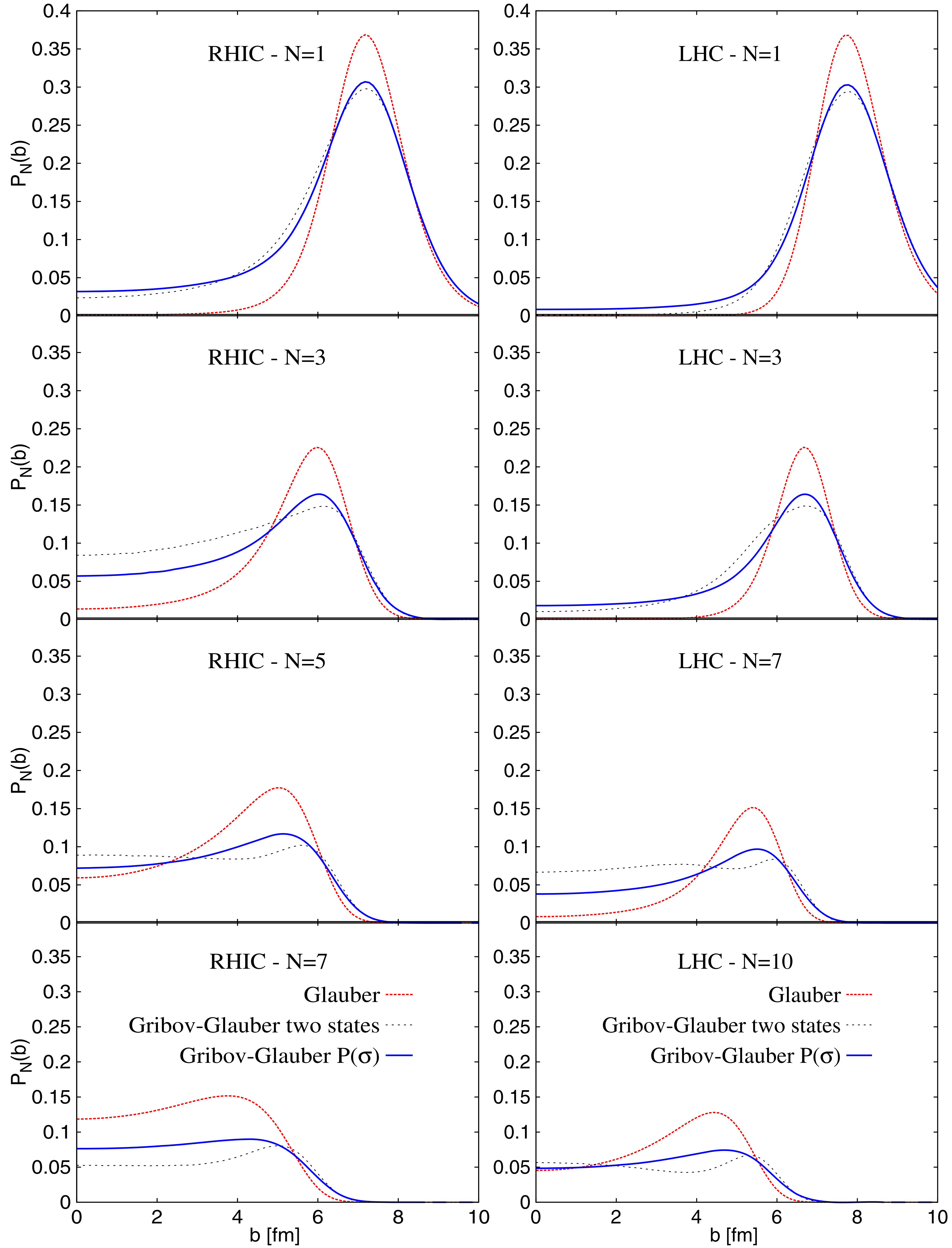
with parameters fixed to satisfy sum rules

Energy/model	Monte Carlo		
	$\langle N \rangle$	$\langle N^2 \rangle$	ω_N
RHIC, Glauber	4.6	31.6	0.51
RHIC, GG2	4.7	38.9	0.74
RHIC, GG $P_h(\sigma_{tot})$	4.8	39.2	0.72
LHC, Glauber	6.7	72.4	0.59
LHC, GG2	6.8	84.2	0.80
LHC, GG $P_h(\sigma_{tot})$	6.8	82.1	0.77

$$\omega_N \equiv \frac{\langle N^2 \rangle}{\langle N \rangle^2} - 1$$

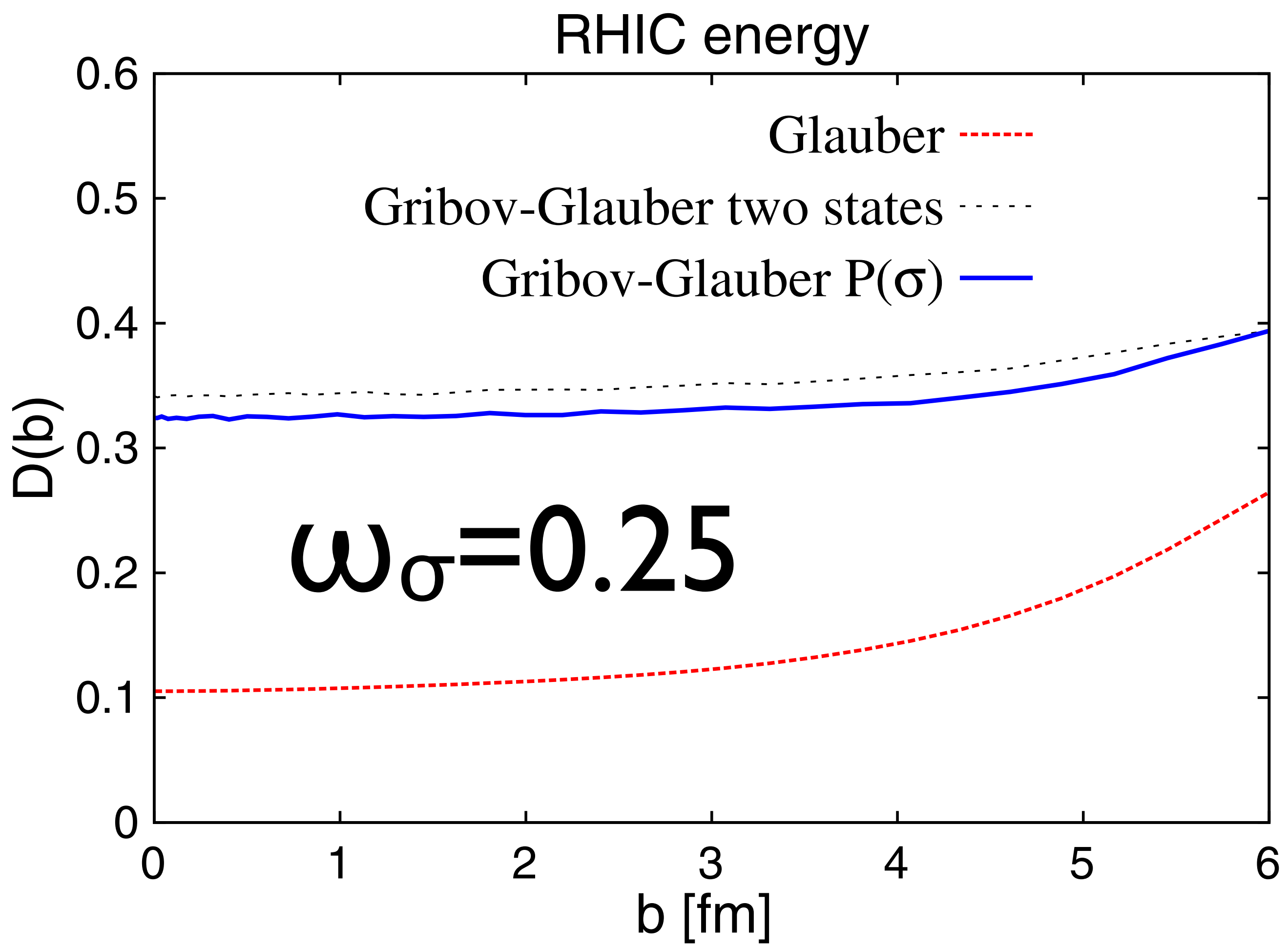
Small effect for <N>

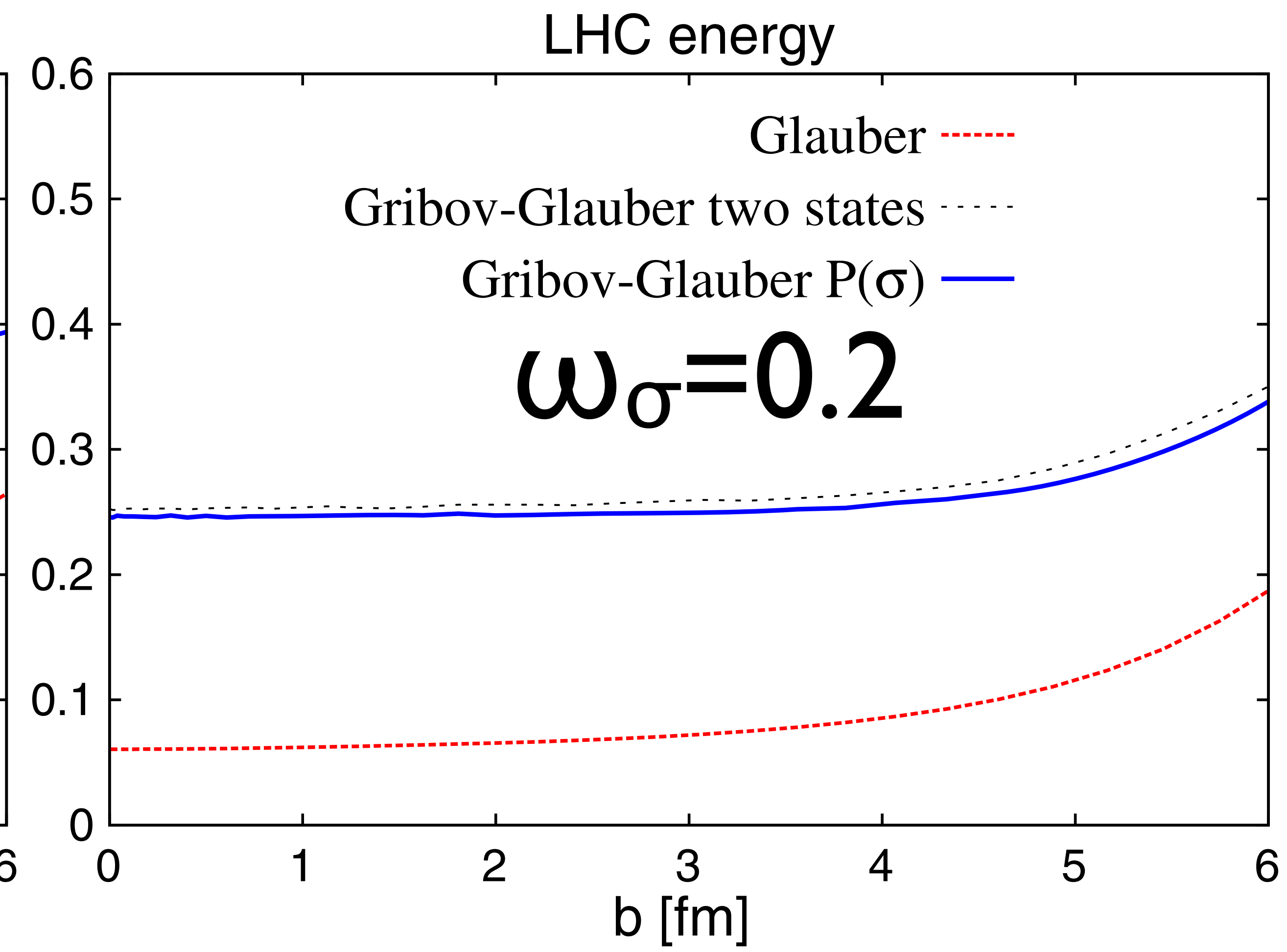
Large color fluctuation effect for dispersion even though in dispersion one integrates over impact parameters. Effect is much larger for fixed b - see below

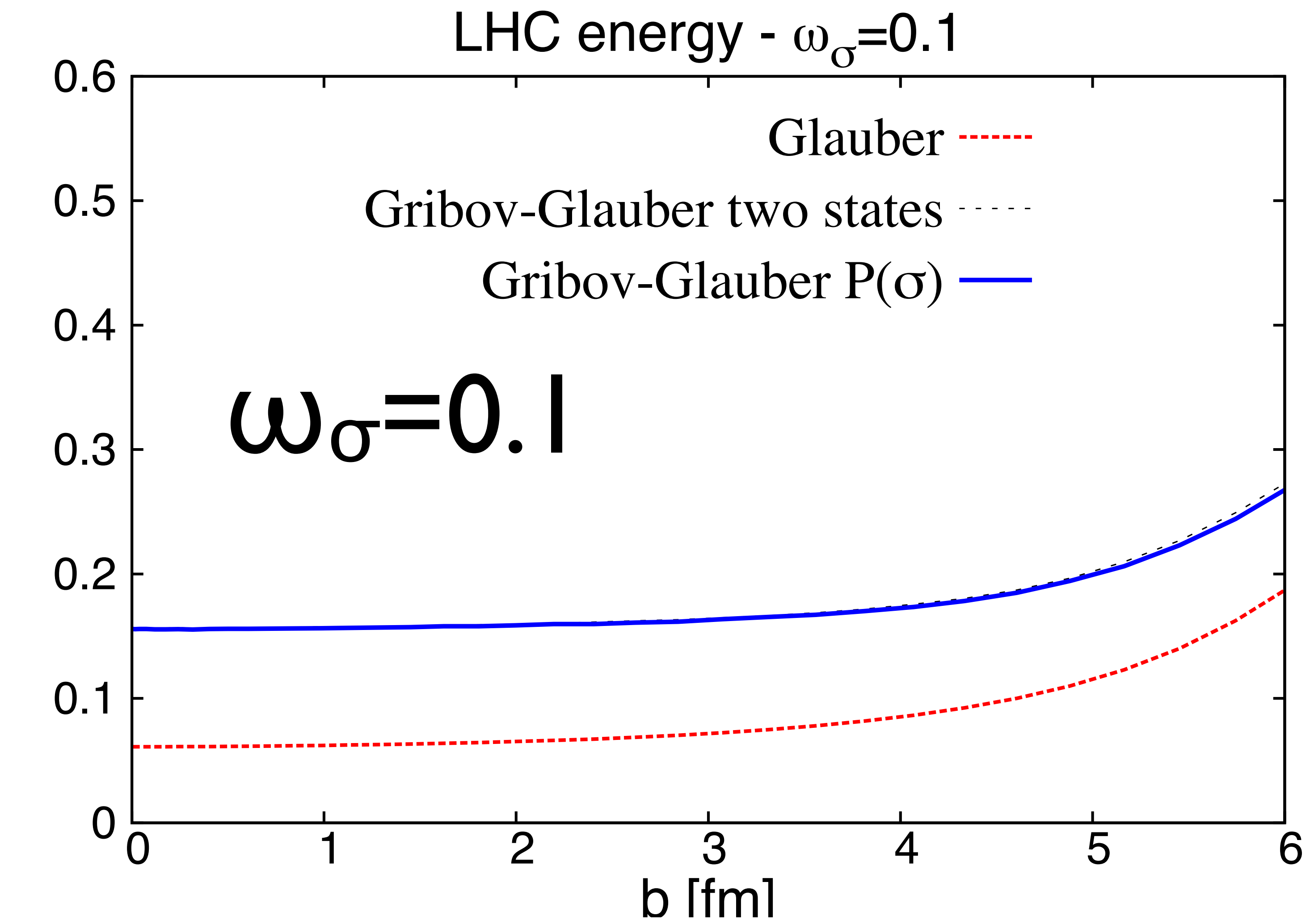


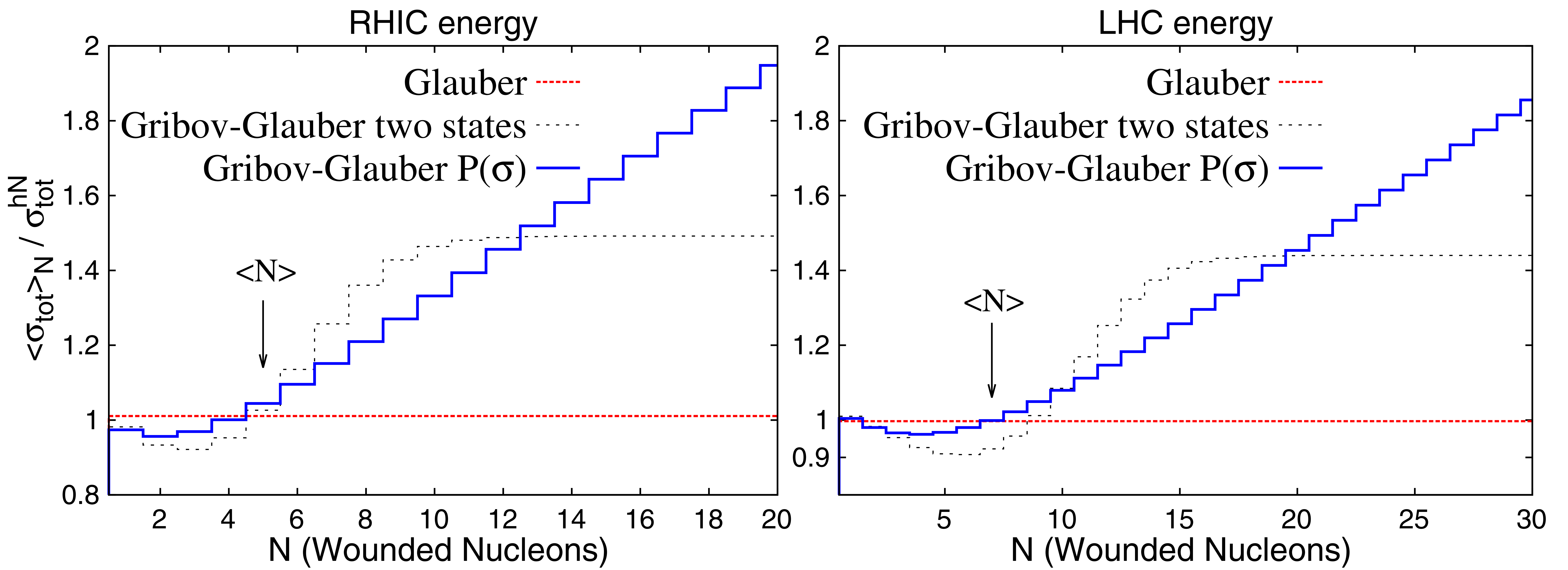
The probability P_N (b) of having N inelastically interacting (wounded) nucleons in a pA collision, vs. impact parameter b, when using simple Glauber (red curves) and a distribution P (σ) (green curves); We show the probabilities P_N (b) for N=1 (top row) for both energies and the curves for N corresponding to ⟨N⟩ and ⟨N⟩±0.5⟨N⟩ (remaining panels); ⟨N⟩ is 5 and 7 for RHIC and LHC energies, respectively

Fluctuations give dominant contribution to fluctuations of N for fixed b







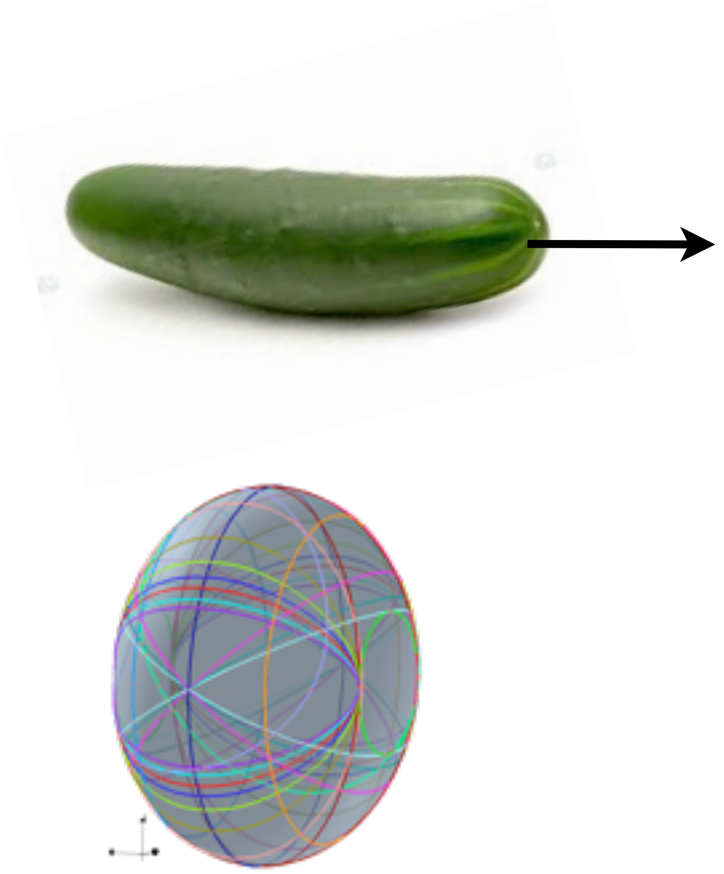


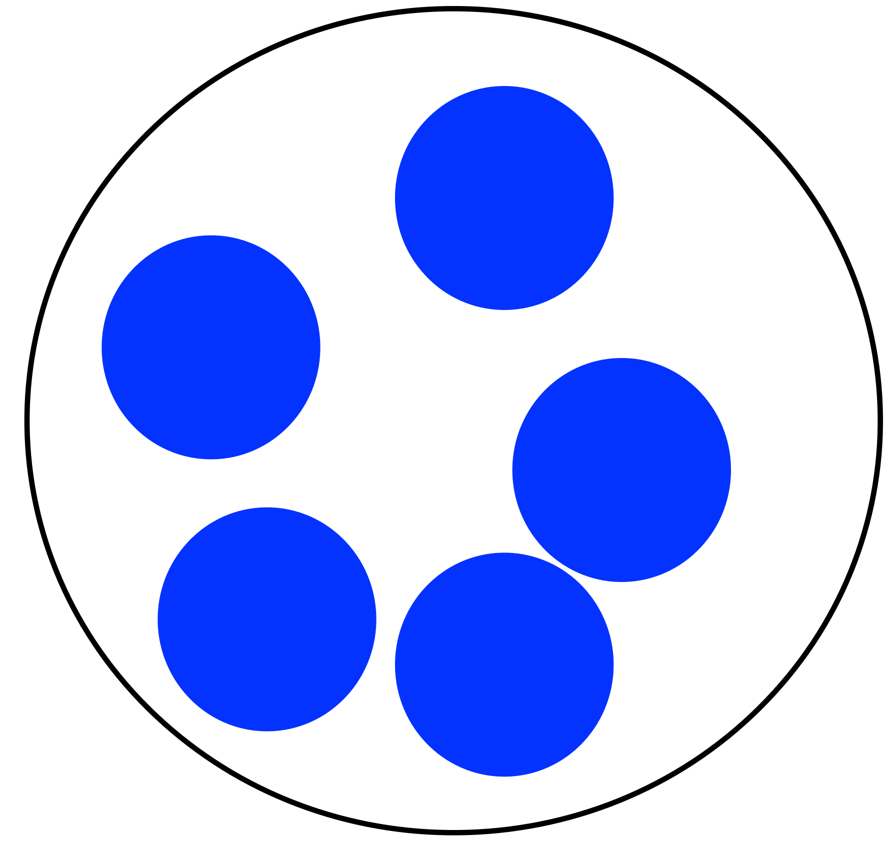
Effect of fluctuations on the event-by-event fluctuating values of cross section. Small number of wounded nucleons, M, selects σ's smaller than average - large M --- - $\sigma > \sigma_{tot}$

$$\frac{\langle \sigma_{tot} \rangle}{\sigma_{tot}^{hN}} \sim 2$$ for N/<N> =4

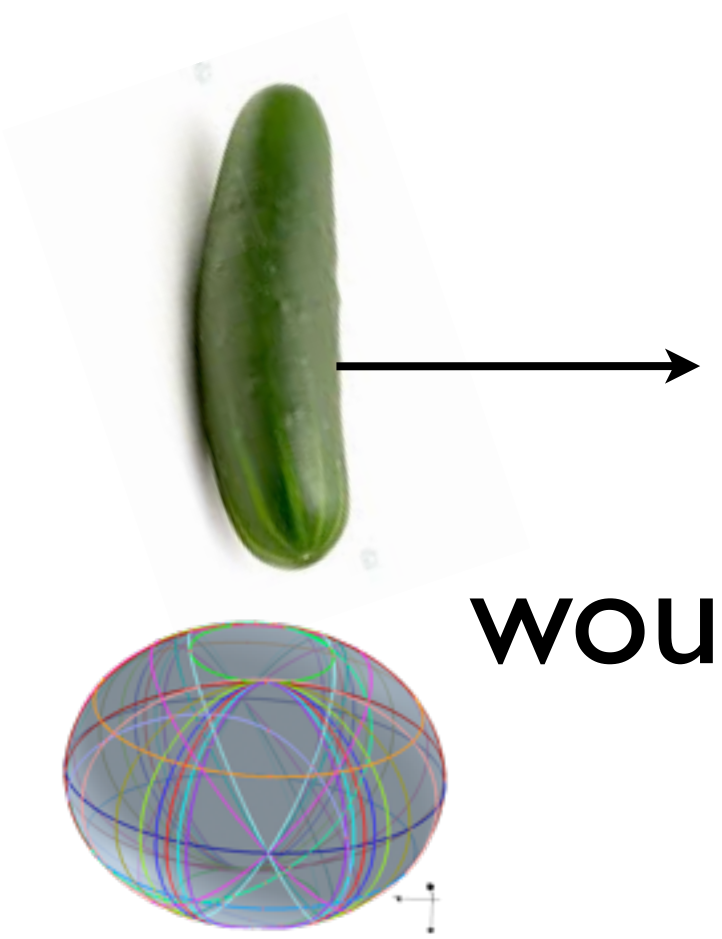
Reminder: RHIC studied d-Au - smaller effect of fluctuations for hard trigger.

Different σ's --- different size, different shape, different parton densities

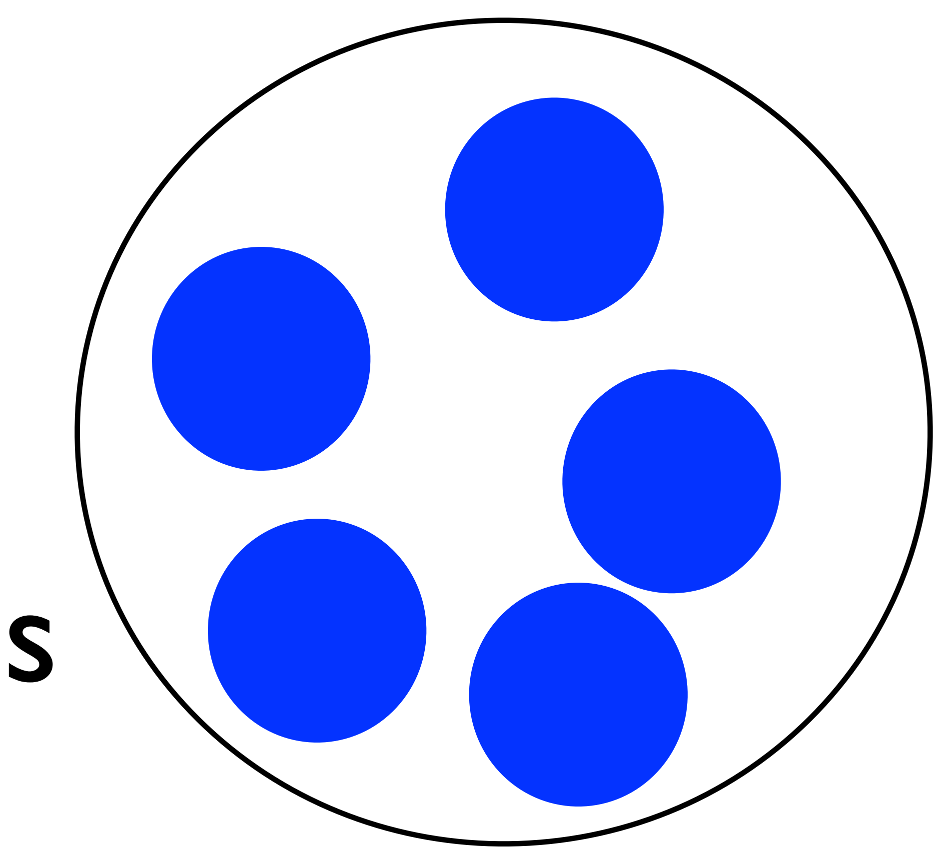




Conditional pdfs



would lead to ridges



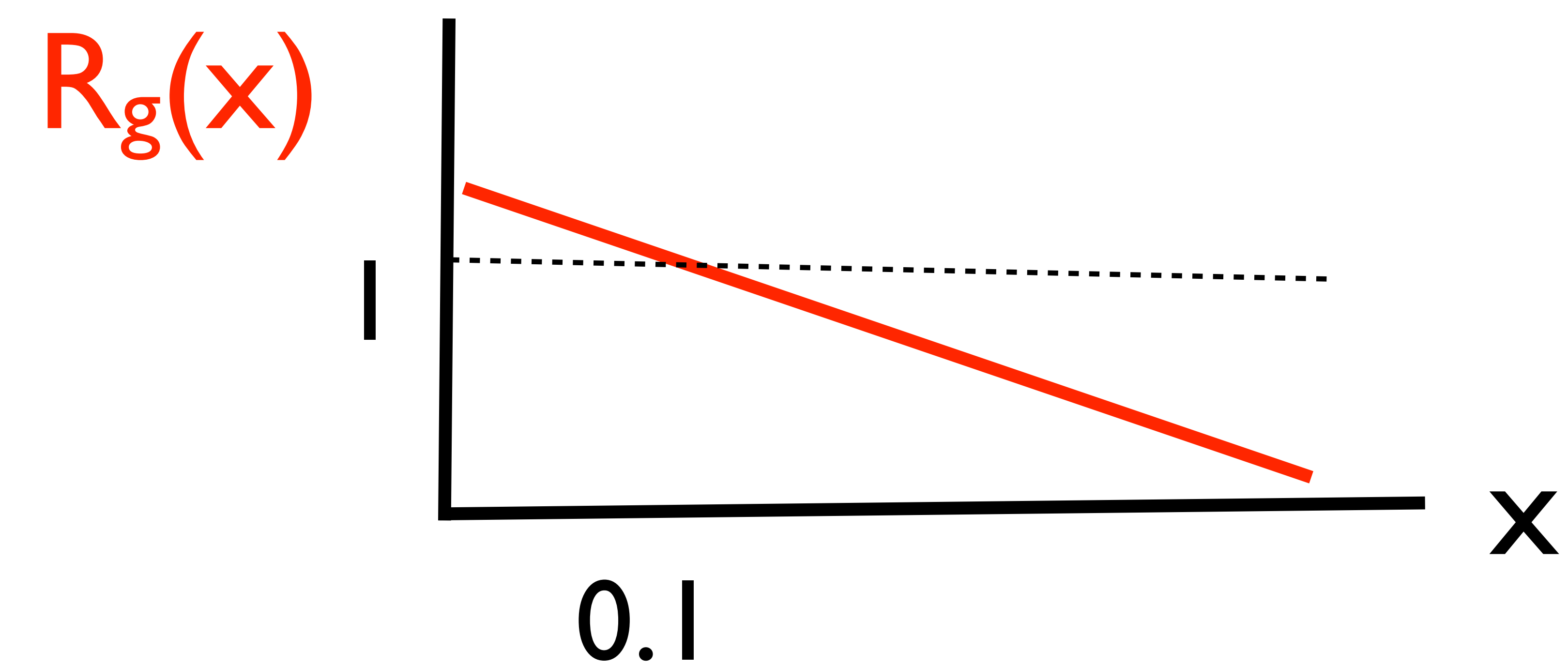
Correlation between the hard and soft components of the pA interaction.

Idea: Use the hard trigger to determine x_p and low p_t hadrons to measure overall strength of interaction σ_{eff} of configuration in the proton with given x_p FS83. *Conditional pdfs*

LHC - jets with large p_t - -- practically no nuclear shadowing effects
RHIC - mixed situation

Expectation: Larger the size, more gluon radiation, softer the x distribution

Illustration



$$G(x, Q^2 \, |\sigma) = G(x, \xi Q^2)$$

$$\xi(Q^2) \equiv (\sigma/\langle\sigma\rangle)^{\alpha_s(Q_0^2)/\alpha_s(Q^2)} \quad where\, Q_0^2 \sim 1\,\mathrm{GeV}^2$$

gives a reasonable magnitude of fluctuations of the gluon density

would result in different parton distribution in nucleons measured with different number of wounded nucleons, with no change in the inclusive case

Alternative strategy - use a hard trigger which selects rare configurations in nucleon which are small size or large size (large number of wounded nucleons?)

The presence of a quark with large $x>0.6$ requires three quarks to exchange rather large momenta, one may expect that these configurations have a smaller transverse size (+ few gluons & sea quarks at low Q scale) and hence interact with the target with a smaller effective cross section: σ_{eff}.

Note: if $x>0.6$ configurations do have a size smaller than average, it would explain the EMC effect (FS83)

Selection of such x seems feasible at LHC. Can it be done at RHIC after forward upgrade?

Generically - there should be correlations between the rate of hard collisions and soft multiplicity - modifications in both nuclear pdfs and nucleon pdfs. Interpretation a bit more complicated at RHIC than at the LHC because of issue of account for energy conservation (PHENIX 1305.3540)

Especially interesting looking at events with the number of wounded nucleons > 1.5 <N>. Changes in both conditional nuclear pdfs, and in proton.

Conclusions on physics opportunities of pA:

- Will produce a novel information on strong interactions in the high gluon density kinematics for fixed nuclear thickness as a function of energy: *parton , groups of partons propagation through media in soft and hard regime including spin effects (I do not large ones - hence not discussed)*

- Will complement pA run at LHC - critical for understanding how small x dynamics changes with energy

- Will allow to measure inelastic diffraction at the highest energy where it is still comparable/larger than e.m. contribution

- Check the color fluctuation dynamics for generic inelastic pA collisions, measure conditional nucleon/ nuclear pdfs.